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FACTORS BY WHICH SHOT PEENING INFLUENCES

THE FATIGUE STRENGTH OF PARTS

By

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## INTRODUCTION

It is somewhat less than a quarter of a century since shot peening was first used consciously to improve the fatigue strength of metal parts. During this time, considerable effort has been spent toward finding the improvement attainable in specific applications and methods for attaining this improvement. While all the factors which affect the improvement are not completely understood, a number of useful ideas concerning the mechanism of improvement have been advanced. The objective of this paper is to review these ideas toward an appreciation of the present status of understanding the effect of shot peening upon fatigue strength.

There are at least three obvious ways in which shot peening may be expected to influence the fatigue strength of a metal part:

1. Each shot makes a slight indentation so that the peening operation roughens a previously polished surface. This would be expected to lower the fatigue strength.

2. Each indentation involves distortion of metal underneath; such distortion produces work hardening (and, sometimes, other structural changes) in near-surface layers. This may increase fatigue strength, or in special circumstances may decrease it.

3. The general yielding of surface metal leaves macroscopic residual-compressive stresses. These stresses are generally considered the most important factor in the improvement of fatigue strength by shot peening.

This separation of influencing factors is admittedly oversimplified, but will afford an approach to an analysis of present knowledge. Some additional factors will be noted subsequent to discussion of these three.

## SURFACE ROUGHENING

In the case of a polished surface, each dent produced by a shot may be considered a source of geometrical stress concentration. Available information is inadequate to give a good estimate of a stress-concentration factor or of a fatigue-notch factor for such dents. However, the impressions are small, well rounded, and overlapping. Taking all these into account, one may speculate that a fatigue-notch factor for a typical shot-peened steel surface might be about 1.10 (see Reference 1). This implies something like a 10% maximum reduction in fatigue strength compared to a polished surface.

The geometrical effect of surface roughening may be estimated in another way. The roughness of a shot-peened surface varies widely with the steel, the shot, and the conditions of peening. However, a fairly typical surface gave a profilometer reading of about 90-microinch rms in contrast to that of a polished fatigue-test specimen (about 6-microinch rms). There have been a number of investigations of the effect of surface roughness, produced by mechanical finishing, on fatigue strength (see, for example, References 2 and 3). These have shown decreases in fatigue strength from 4 to 35 per cent for differences in surface of the order of those mentioned for polished versus shot-peened bars. This would correspond to a fatigue-notch factor in the range 1.04 to 1.40.

Thus, there is reason to believe that the geometrical effect of surface roughening by peening would, by itself, decrease fatigue strength. The decrease might be in the range of 4 to 40 per cent. It would be interesting to seek, by suitably planned experiments, a more definite evaluation of this factor.

## SURFACE STRENGTHENING

The distortion of grains at and near the surface changes their physical properties. Metallographic examination (see, for example, Reference 4) discloses evidence of change of structure beneath the surface. In some instances (Reference 5), hardness tests show metal hardened greater than that to which changes of shape of grains can be detected.

Change in shape, size, and orientation of grains may be expected to influence the fatigue strength in the region of change. It is very difficult to separate effects of such structural changes from effects of concurrent residual stresses resulting from the peening. Thum and Bautz (Reference 6) attempted to separate similar effects in surface-rolled specimens. Tests were made on as-rolled specimens and on specimens rolled and stress relieved (to some extent) by boring out the centers. It was concluded that about one-fifth of the increase in reversed-bending fatigue strength was due to the increased hardness (the other four-fifths being due to favorable residual stresses). Horger and Maulbetsch (Reference 7) made some very interesting tests on small specimens machined from surface-rolled axles. Figure 1 shows some of their observations and indicates definite increase in fatigue strength with cold working under conditions where at least a large part of the residual stress was removed by the sectioning. They also found somewhat larger increase in fatigue strength with cold working by stretching the bars.

Thus, it appears that cold working of surface layers by shot peening may, apart from the macroscopic residual stress produced by the peening, tend toward increased fatigue strength of the part. It is very difficult to suggest even an approximate value for the magnitude of this effect. Arguments have been advanced (see, for example, Reference 10) for supposing that the increase from cold working alone is small. The amount may, in many cases, be of the order of the decrease from the geometrical effect of surface roughening. In that event, these two factors would tend to balance each other so that a determining factor would then be the residual stress induced by the peening.

## RESIDUAL STRESS

Deformation of surface layers during peening involves plastic "flow" of metal near the surface, which stretches the subsurface core. Subsequently, the elastic core material tries to force the deformed material back into shape. As a result, surface metal is in compression and core material in tension after the peening. The importance of residual compressive stresses near the surfaces of metal parts has been discussed extensively by J. O. Almen (Reference 8).

Actually, the residual stress is biaxial at the surface and triaxial beneath (see Reference 5). For the moment, we shall neglect this and, over-simplifying the situation, consider just the longitudinal residual stress in a simple bar specimen.

Figure 2 shows the residual stress pattern that might exist in a bar of steel shot peened on the top side only. Let us consider the stresses at various locations in this bar when it is subjected to repeated bending so that the load stress at the top varies from zero to 200-ksi tension. When the applied load is zero, the stresses will be those indicated by the broken line labelled "residual stress". At maximum load, the stresses will be those shown by the solid line labelled "resultant stress"*.

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*A further simplification in this discussion is the assumption that the residual stress does not change during the repeated-loading test.

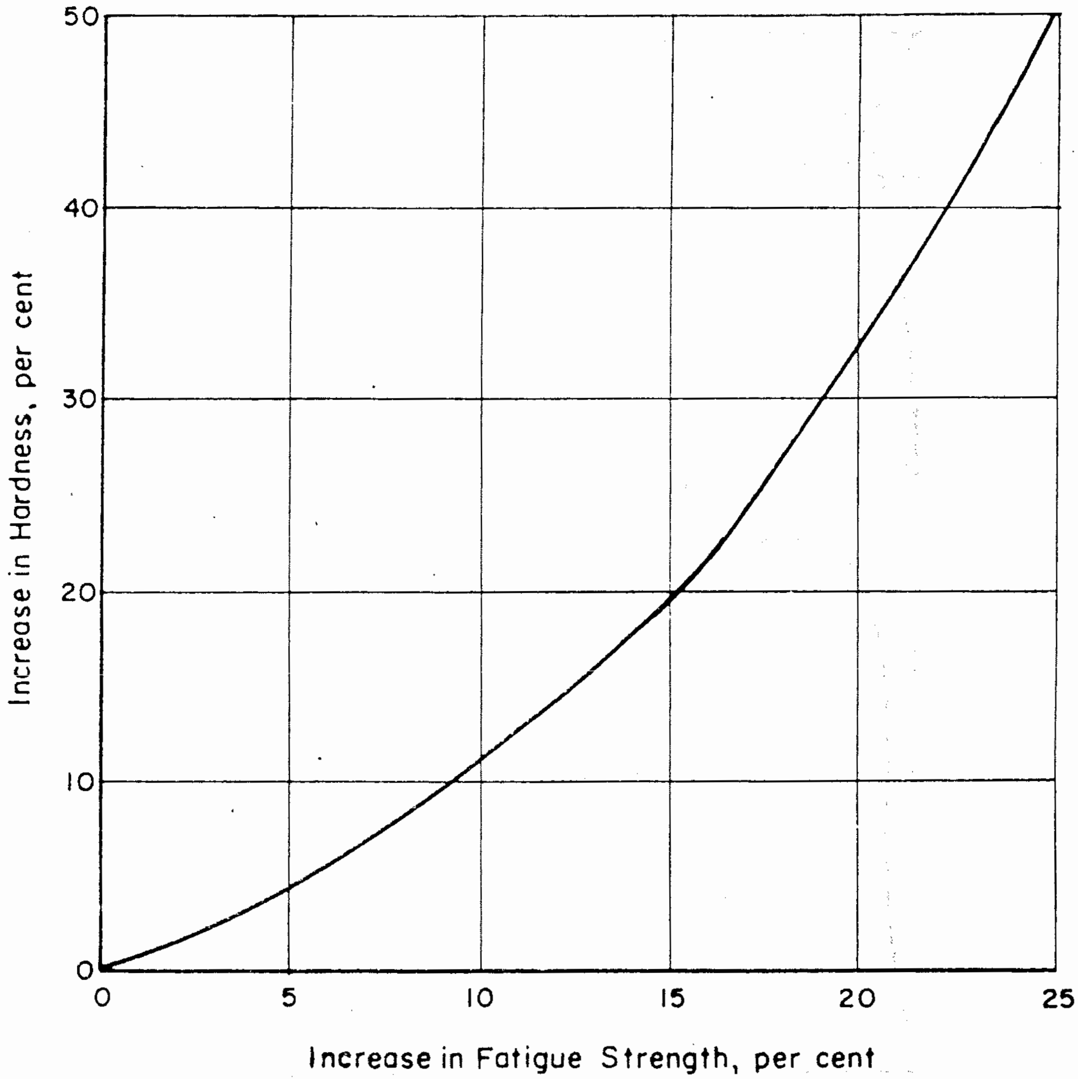


FIGURE 1. INCREASE IN FATIGUE STRENGTH WITH COLD WORKING, HORGER AND MAULBETSCH (REF 7)

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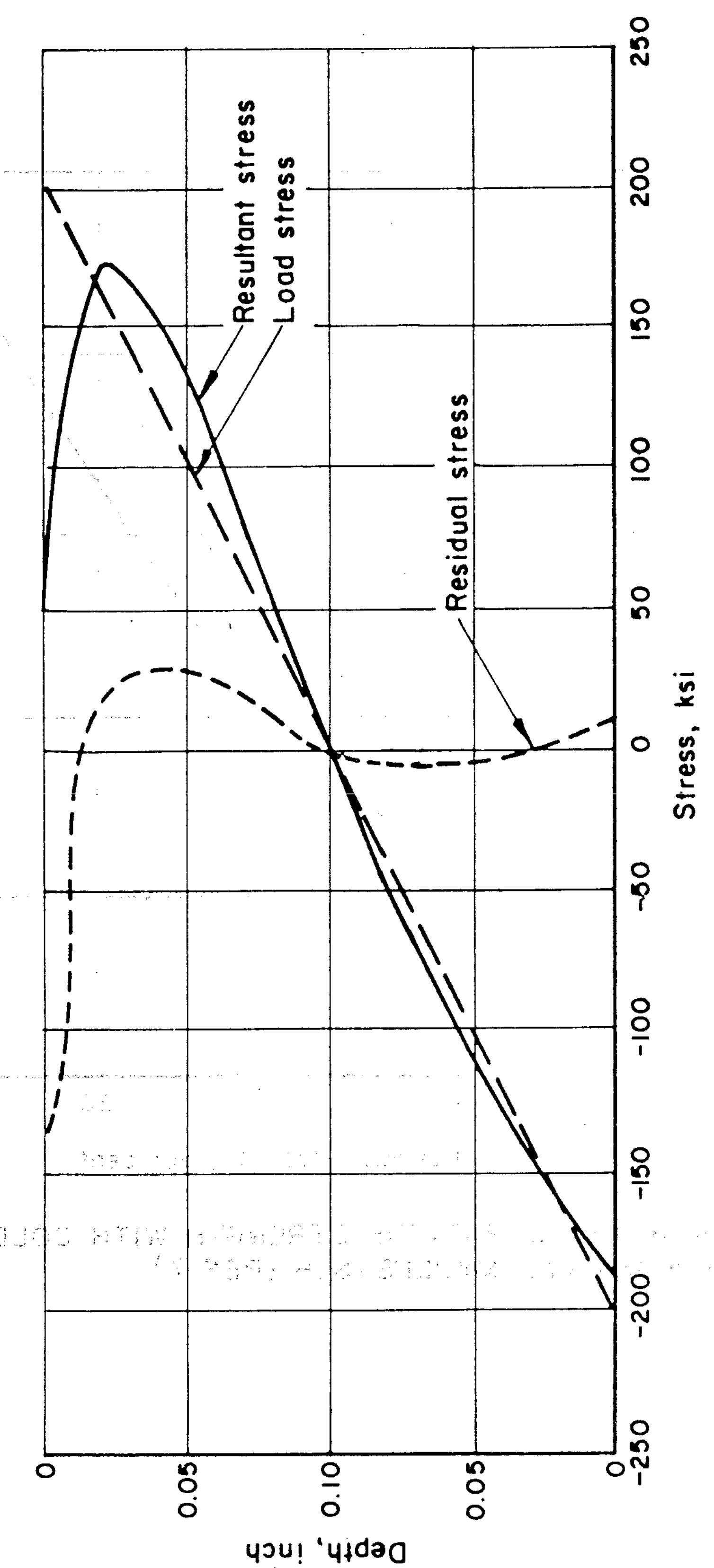


FIGURE 2. SCHEMATIC DIAGRAM OF STRESSES IN SHOT-PEENED BAR

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From Figure 2, one can make up a table of values of cyclic stresses in the peened bar and corresponding stresses which would occur in a similarly loaded unpeened bar. Such values are shown in the following tabulation. It may be noted, at most points in the upper half of the bar, that both maximum and minimum stresses are different from the two cases. The residual stress (being considered constant) has shifted the total mean stress in the loading cycle, but has not influenced the amplitude of stress.

| Depth Below Top Surface, inch | Stresses, ksi | | | |
|---|---|---|---|---|
| | Unpeened Bar | | Peened Bar | |
| | Minimum | Maximum | Minimum | Maximum |
| 0 | 0 | +200 | -140 | + 60 |
| 0.01 | 0 | +180 | - 75 | +105 |
| 0.02 | 0 | +160 | + 15 | +175 |
| 0.03 | 0 | +140 | + 25 | +165 |
| 0.04 | 0 | +120 | + 30 | +150 |
| 0.05 | 0 | +100 | + 30 | +130 |
| 0.06 | 0 | + 80 | + 25 | +105 |
| 0.08 | 0 | + 40 | + 10 | + 50 |
| 0.10 | 0 | 0 | 0 | 0 |

In evaluating the influence of the residual stress upon the fatigue strength of the bar, it seems in order to consider the influence of mean stress upon stress amplitude in fatigue. Figure 3 (from Reference 9) shows this influence for one steel ---in the form of a modified Goodman-type diagram. Goodman diagrams are not available for many materials, and none was found for the particular steel considered in this example. The usual expedient (drawing straight lines through a value for tensile strength and values from fully-reversed-loading fatigue tests) can serve for the present discussion. Figure 4 illustrates such a diagram.

Before considering the effect of peening, consider an unpeened bar loaded so the top surface varies from zero to tension (note on Figure 4, the line through the origin and Point A). At a maximum stress level of 200 ksi (mean stress of 100 ksi plus stress amplitude of 100 ksi), failure will occur at Point A in about 15,000 cycles. This is the lifetime expected for an unpeened bar. For a reason that will appear shortly, it is desirable to note conditions corresponding to a lifetime of 200,000 cycles; these are as follows: mean stress of 85 ksi, stress amplitude of 85 ksi, and maximum stress of 170 ksi.

Figure 5 illustrates a part of this same Goodman diagram with a heavy curve representing stress conditions at various depths in the shot-peened specimen. This was obtained from the tabulation on this page; the upper left starts at the surface, the line bends back sharply at a depth between 0.02 inch and 0.03 inch below the surface. It appears that this curve will just touch a Goodman line corresponding to a lifetime of about 200,000 cycles. This point of intersection will correspond to: a depth about 0.015 inch, a mean stress about 97 ksi, and a stress amplitude about 80 ksi.

Thus, the calculation indicates a lifetime of about 200,000 cycles for the shot-peened specimen compared to about 15,000 cycles for an unpeened specimen. The nominal maximum stress for the peened specimen is 200 ksi; for an unpeened specimen living as long, it would be about 170 ksi. Peening may be said to have increased the lifetime some 130 per cent, or to have increased the loading stress withstood to a specified lifetime of about 15 per cent.

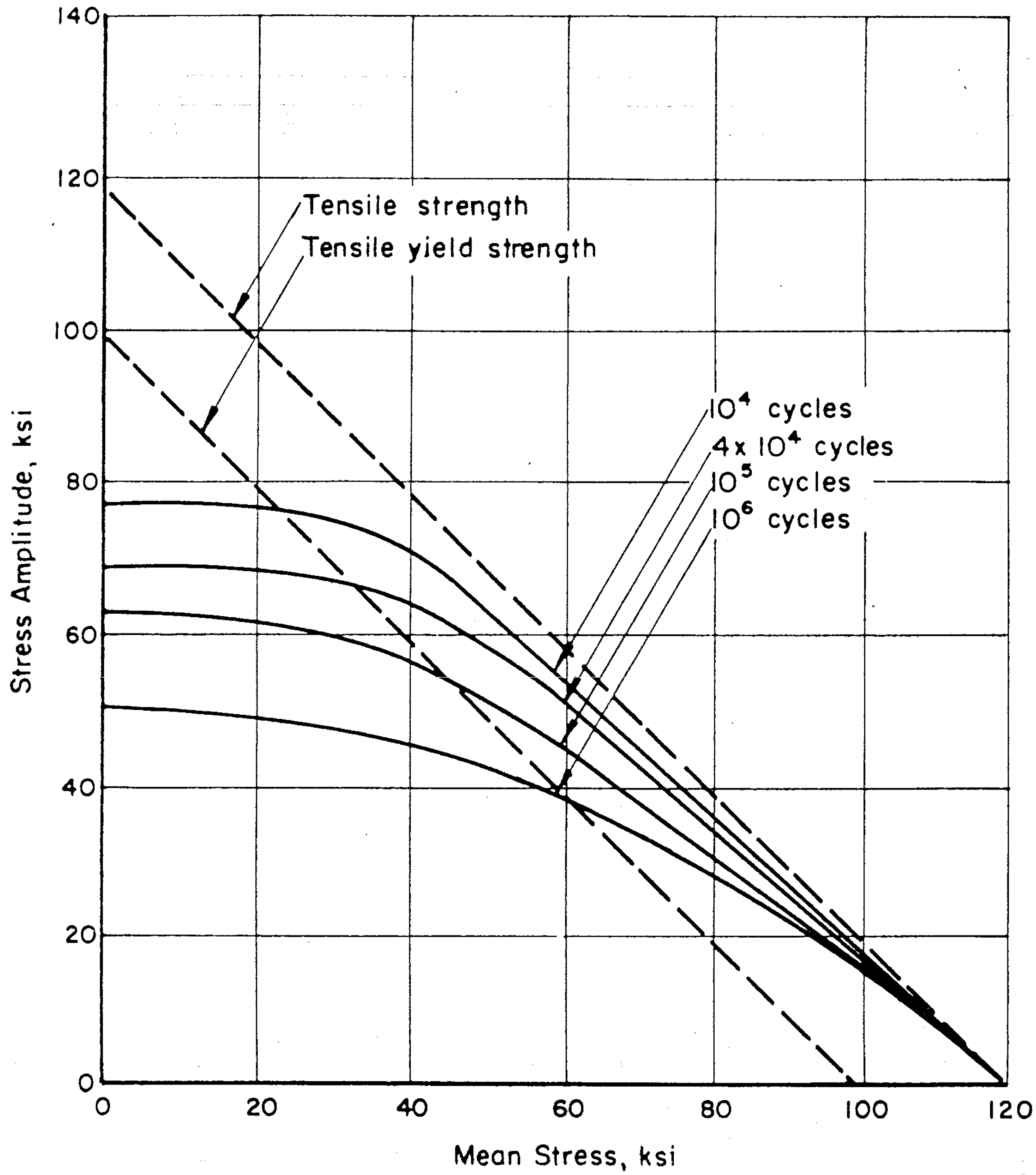


FIGURE 3. GOODMAN DIAGRAM FOR A NORMALIZED SAE 4130 STEEL (REF. 9)

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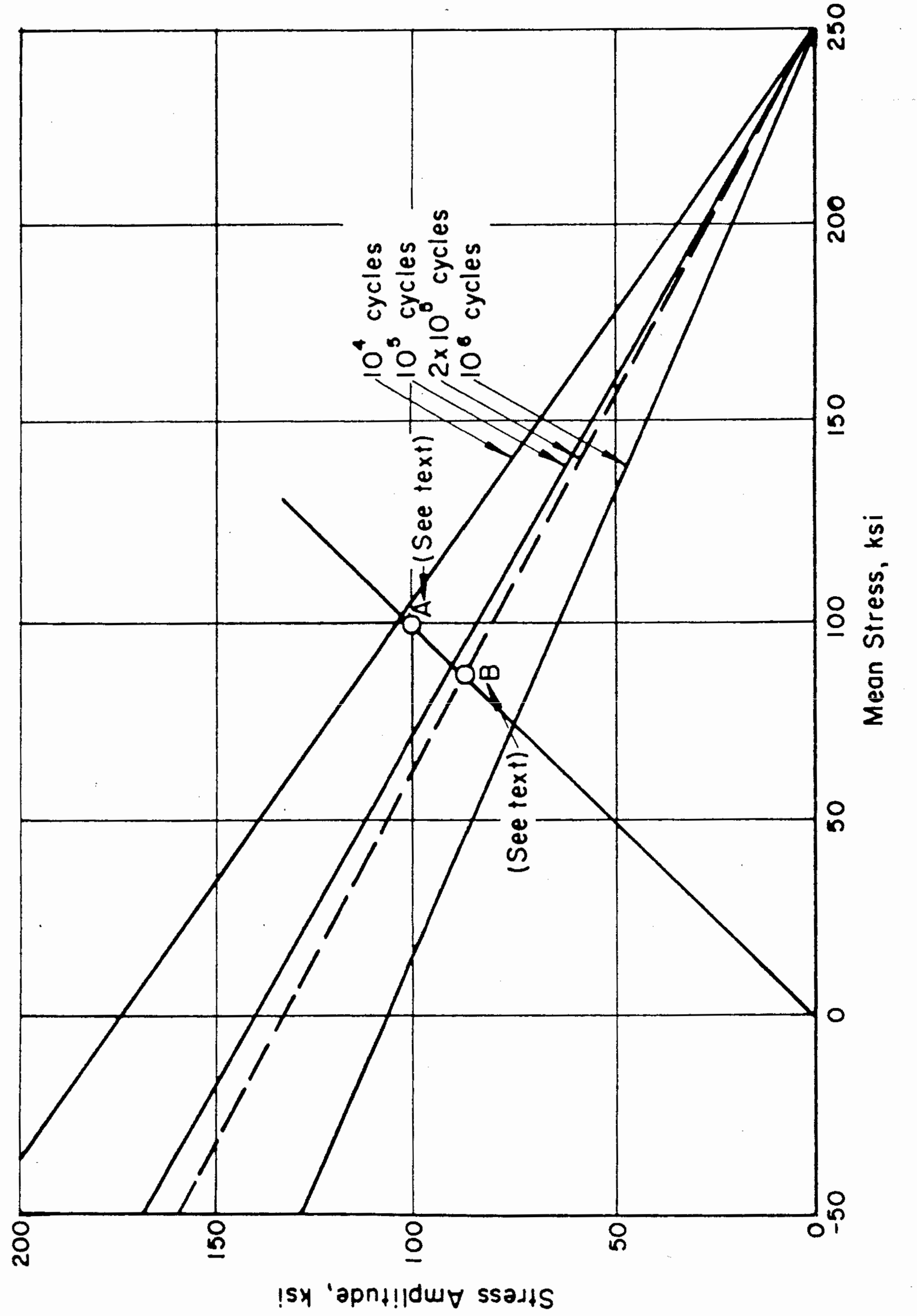


FIGURE 4. APPROXIMATE GOODMAN DIAGRAM FOR HIGH-STRENGTH STEEL

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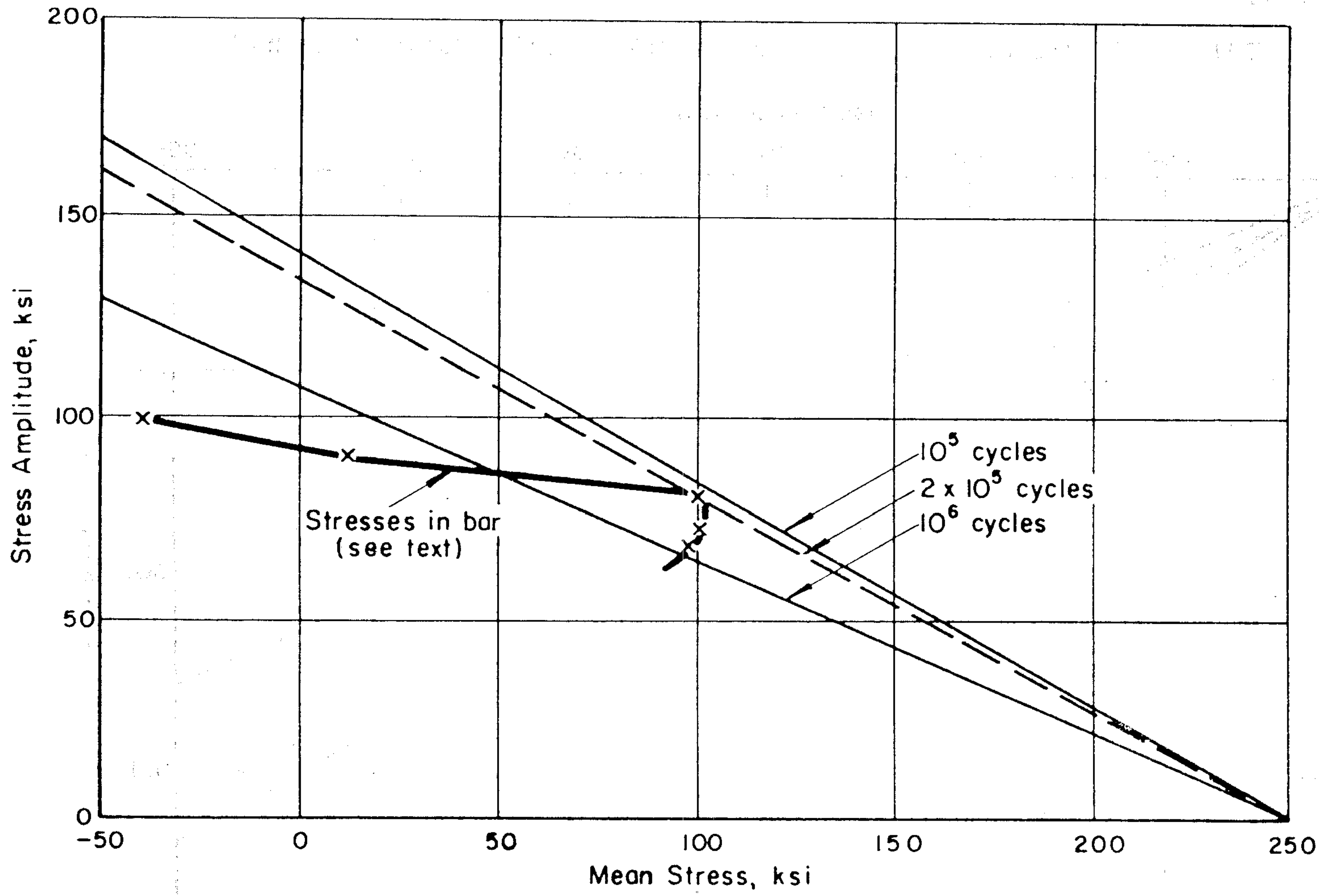


FIGURE 5. STRESSES IN SHOT-PEENED BAR ON GOODMAN DIAGRAM

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It may be noted that the calculation predicted a subsurface failure. Such failure is found often in shot-peened specimens (especially in stress-peened ones which have high residual stresses). Figure 6 is a photograph showing the nucleus of fatigue failure in a shot-peened spring leaf at a subsurface inclusion.

This simplified calculation shows a number of items useful as guides in respect to practical improvement of fatigue life by shot peening. Insofar as residual stresses are concerned, it appears that improvement should be expected mainly when the loading produces a stress gradient. The bar used as an example might have its tension-tension fatigue strength lowered by peening; it would be expected to fail, under such loading, beneath the surface at the region of maximum residual tension. Under fully reversed bending, it would be expected to fail at the bottom unpeened surface (at a slightly lower lifetime than that of an unpeened bar). In general, peening should be effective in bending and torsion where there is a considerable stress gradient. However, it should be helpful also in axial loading of notched specimens where the geometry imposes a gradient of loading stress. The approach used in this example could be applied to other loading conditions. At present, information is scarcely adequate to examine its validity in a relatively simple situation.

## ADDITIONAL FACTORS IN REGARD TO RESIDUAL STRESS

The example just given was oversimplified in several respects.

For one thing, an oversimplified approximation to the Goodman diagram was used. The author was unable to find an instance in which there was experimental evidence concerning the improvement in fatigue strength by shot peening, the residual stress actually produced by the same peening, and a Goodman diagram for the steel in the same general condition.

Figure 2 suggests that the straight-line diagram may not be a very good approximation for the present purpose. However, information about the effect of mean stress upon fatigue strength is increasing, and this oversimplification can be avoided when adequate data are available.

Next, it was assumed that the residual-stress pattern did not change during the course of the fatigue test. This is not always so. Moore (Reference 5) states: "Test data on this are meager, but a few tests at the University of Illinois showed that even a single cycle of applied stress above the yield point of the peened metal removed the greater part of the longitudinal residual stress . . . .". "No serious reduction was found for applied stresses lower than about one-third of the yield strength . . .". The general problem of allowing for alleviation of the favorable residual stress during loading is not dissimilar for the problem of allowing for alleviation of notch stress concentrations by local yielding at relatively high loads. It is quite possible that future research can develop useful methods of allowing for this effect in estimation of improvements in fatigue strength by shot peening.

Again, in the numerical example, the transverse residual stresses introduced by peening were neglected. In most reports of measurement of peening stresses, these have not been measured. There is relatively little information about biaxial residual stresses from peening or about the effect of biaxiality of residual stresses from any source upon fatigue strength. However, considerable work is being done upon the effect of combined stresses in fatigue. In current work at Battelle, sponsored by the Norton Company, biaxiality of grinding stresses (as determined by Dr. H. Letner of the Mellon Institute) is being considered in the general problem of analyzing effects of grinding upon fatigue strength. Similar analysis could be made with respect to shot-peening residual stresses.

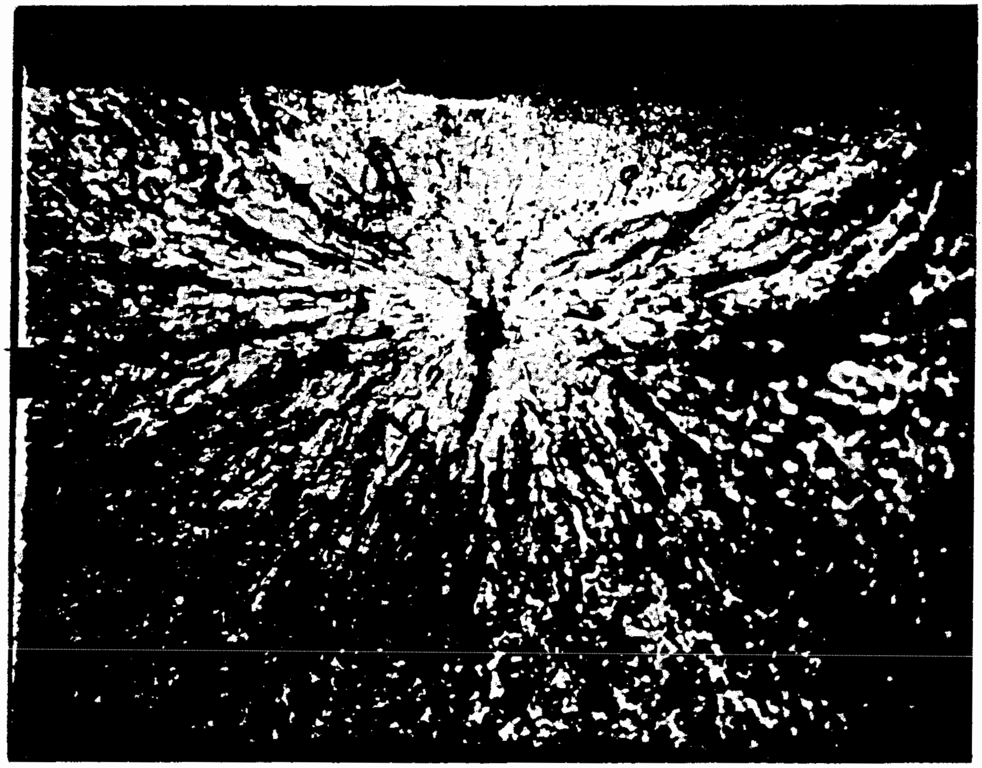

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FIGURE 6. SUBSURFACE NUCLEUS OF FATIGUE FAILURE IN A SHOT-PEENED SPRING LEAF

(Courtesy of Standard Steel Spring Division, Rockwell Spring and Axle Company.)

## ADDITIONAL FACTORS IN PRACTICE

To this point, consideration has been directed to somewhat idealized situations. It has been tacitly assumed that the surface prior to peening was smooth, polished, free from decarburization, etc., so that fatigue improvement was simply based upon comparison with fatigue strengths of polished specimens. It also was tacitly assumed that peening was near optimum (with complete and uniform coverage, of suitable intensity to provide high residual stress without overpeening, etc). In view of the objective of this paper, departures from these conditions may be considered as additional complications in analysis; nevertheless, these complications may have great practical significance.

Peening has been effective on various types of surfaces. Carburized gears, decarburized springs, induction-hardened specimens, a notched flame-hardened specimen, straightened automobile axles, and other parts have been reported to have received increased fatigue resistance from shot peening (Reference 11). Actually, one of the advantages of shot peening is its usefulness in improving parts whose surfaces have not been painstakingly polished. A discussion of the effect of shot peening on various types of surfaces from the approach considered in this paper would require detailed characterization of each surface considered. So extensive a discussion is beyond the scope of the present paper and, to a large extent, beyond the scope of present knowledge of surfaces. There is, however, no apparent reason to doubt that analysis of such factors in the action of shot peening, as those mentioned for polished surfaces, should be helpful toward understanding potential effects of peening upon other surfaces. More research along these lines should be profitable toward better and wider usage of shot peening in many practical applications.

There has been considerable discussion in the literature concerning the importance of complete coverage in shot peening to improve fatigue resistance. An experiment performed at Battelle Institute several years ago, under sponsorship of the Standard Steel Spring Company (now a Division of the Rockwell Spring and Axle Company), graphically illustrates the effect of lack of complete coverage in shot peening spring leaves. A number of leaves were shot peened with little squares of adhesive applied to prevent peening of localized areas. In fatigue tests, specimens failed with cracks originating at the unpeened regions. Even when areas as small as about 1/10-inch square were unpeened, the leaves failed at approximately the same lifetime as that of the completely unpeened specimens. Figure 7 illustrates two failed specimens from this experiment. The leaf on the left side of the figure failed through the unpeened square area; the leaf on the right side failed through a small unpeened area near its upper right-hand edge.

Numerous observations have suggested that for a specific application there is an optimum peening. Too-low intensity of shot and too-few passes do not produce as extensive work hardening and as high and deep compressive stresses as would give maximum improvement in fatigue resistance. Intentional overpeening was tried in some experiments by the Standard Steel Spring Division of Rockwell Spring and Axle Company. Figures 8 and 9 show some of the results obtained by peening spring leaves with several passes of very heavy shot at high intensity. Figure 8 illustrates (note the arrows) metal folds present over a major portion of the peened tension surface of an untested leaf. Figure 9(a) is a micrograph showing a cross section of one of these folds and a subsurface crack. Figure 9(b) shows this same section after etching. Etching showed no evidence of internal scale or decarburization; this indicates that the crack was created after heat treatment and, therefore, was a result of the overpeening. As evident in Figure 8, the surface folds had random orientation; some would be critically oriented so as to initiate fatigue cracks under repeated loading.

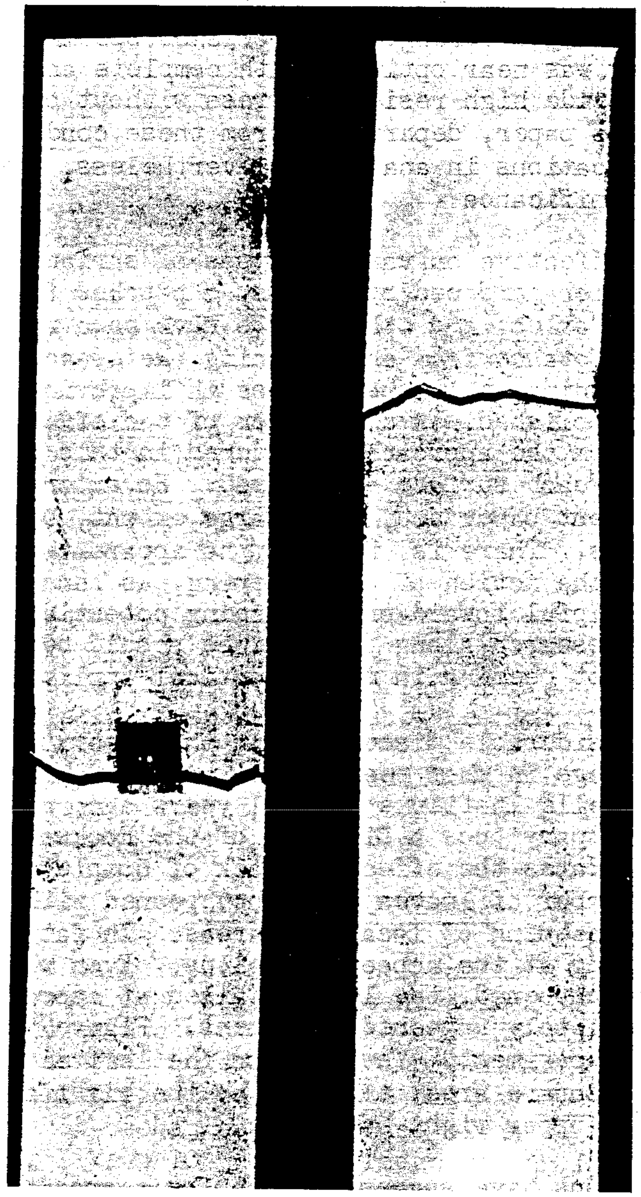

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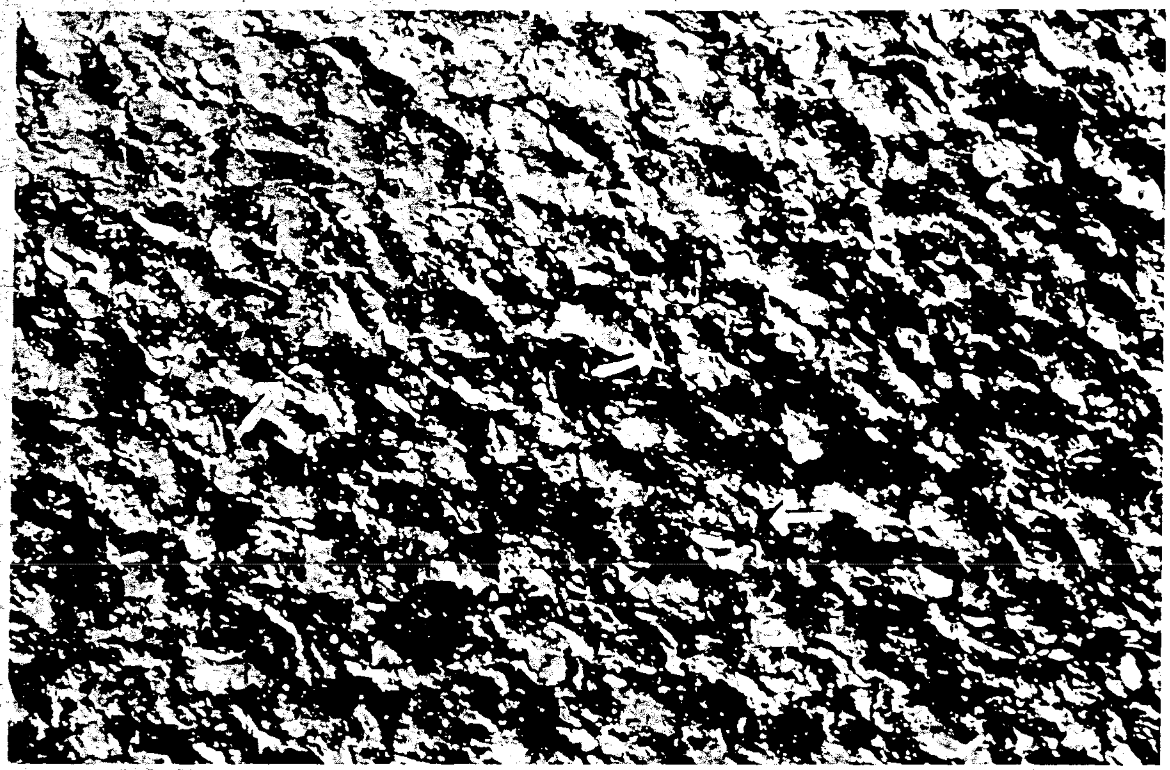
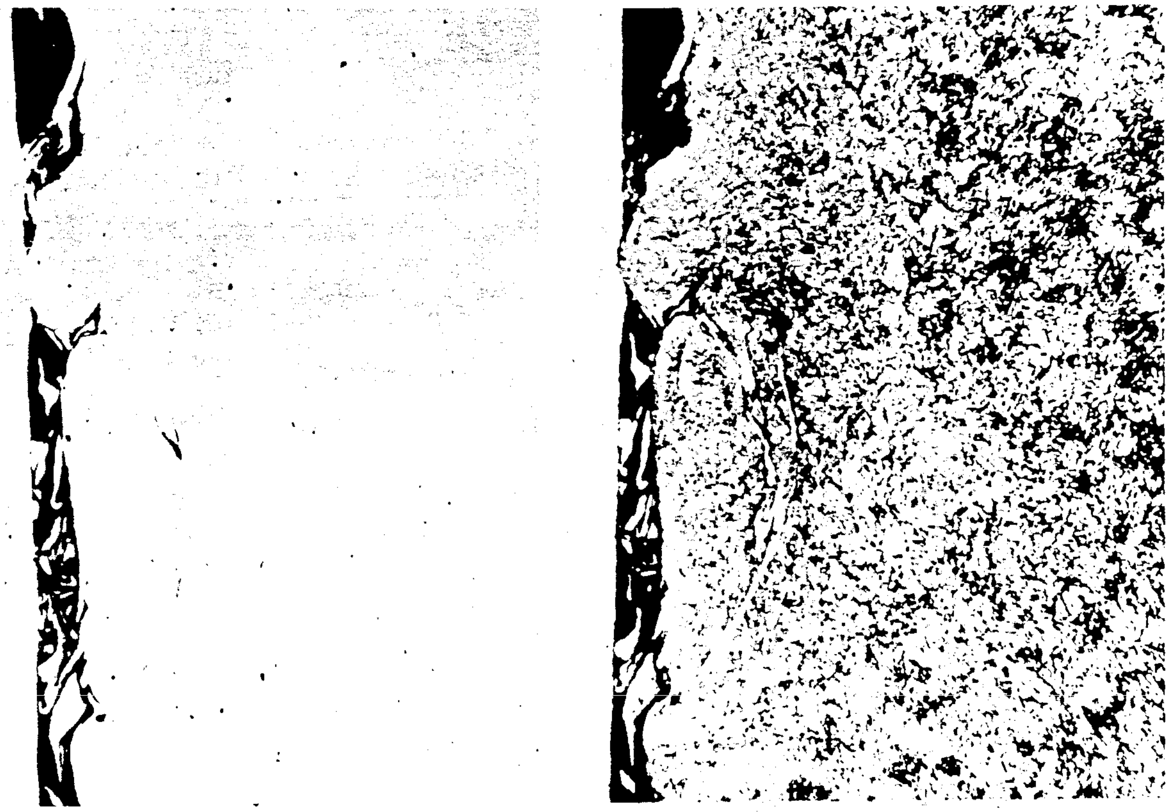
FIGURE 7. EFFECT OF LACK OF COVERAGE IN SHOT PEENING SPRING LEAVES (SEE TEXT)



15X N17328

FIGURE 8. METAL FOLDS IN THE INTENTIALLY OVERPEENED SURFACE OF A SPRING LEAF

(Courtesy of R. S. Komarnitsky, Research and Development Laboratory, Standard Steel Spring Division of the Rockwell Spring and Axle Company.)



200X N17329 200X N17329

(a) Just before etching (b) After etching

FIGURE 9. CROSS SECTION THROUGH ONE OF THE FOLDS IN FIGURE 8

(Courtesy of R. S. Komarnitsky, Research and Development Laboratory, Standard Steel Spring Division of the Rockwell Spring and Axle Company.)

## CONCLUDING REMARKS

Shot peening to improve the fatigue resistance of metal parts has been actively practiced for less than a quarter of a century. In this time, there has been a great deal of development of methods of peening and of numerous practical applications.

This development of peening has resulted in partial understanding of the mechanism by which shot peening contributes to improvement in fatigue resistance. Three factors have been mentioned: (1) surface roughening, which may decrease fatigue resistance; (2) surface work hardening, which contributes to increasing fatigue resistance; (3) residual stresses, which increase fatigue resistance under loadings that give stress gradients. While it is difficult to prove, it is commonly agreed that the third factor is the most important. Future research could clarify this point.

The general manner in which residual stress from peening may increase the fatigue strength of a part can be understood in terms of a Goodman diagram showing the effect of mean stress upon fatigue strength of the metal peened. Existing data are inadequate to indicate the full usefulness or possible limitations of this approach. It is believed that critical experiments could be designed to study the relation of peening stresses to fatigue strength on the basis of a Goodman diagram.

Relatively little quantitative work has been done upon the biaxiality of stresses produced by peening and the relation of such biaxiality to fatigue strength under various kinds of loading. Increasing knowledge of the effect of combined stresses on fatigue should provide a logical approach to this study.

There are a number of complicating factors in many applications of shot peening that are beyond the present potentialities of quantitative prediction. It does not seem likely that within the immediate future it will be feasible to predict fatigue behavior and its improvement by shot peening to a degree that would make experimental tests in any new application unnecessary. Nevertheless, progress in understanding the mechanism may be made. Such understanding will guide necessary empirical testing, and may be expected to reduce the number of experiments required to develop a new application of shot peening.

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